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# Direct Magnetic Imaging of Ferromagnetic Domain Structures by Room Temperature Scanning Hall Probe Microscopy Using a Bismuth Micro-Hall Probe

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A bismuth micro-Hall probe sensor with an integrated scanning tunnelling microscope tip was incorporated into a room temperature scanning Hall probe microscope system and successfully used for the direct magnetic imaging of microscopic domains of low coercivity perpendicular garnet thin films and demagnetized strontium ferrite permanent magnets. At a driving current of 800 $\mu$A, the Hall coefficient, magnetic field sensitivity and spatial resolution of the Bi probe were $3.3 \times 10^{-4}$ $\Omega$/G, 0.38 G/$\sqrt{\text{Hz}}$ and $\sim 2.8\,\mu$m, respectively. The room temperature magnetic field sensitivity of the Bi probe was comparable to that of a semiconducting 1.2 $\mu$m GaAs/AlGaAs heterostructure micro-Hall probe, which exhibited a value of 0.41 G/$\sqrt{\text{Hz}}$ at a maximum driving current of 2 $\mu$A.

KEYWORDS: Hall probes, scanning Hall probe microscopy, bismuth, ferromagnetic domains, garnets, permanent magnets

An extensive range of technology, including magnetic force microscopy, scanning superconducting quantum interference device (SQUID) systems and semiconducting Hall probes, is currently available for measuring localized magnetic field fluctuations in close proximity to the surfaces of magnetic materials.[1)] Recently, we reported on the development and characteristics of a new room temperature scanning Hall probe microscope system (RT-SHPM) for directly imaging magnetic field fluctuations at the surfaces of magnetic recording media, uniaxial garnet thin films and permanent magnets, where a GaAs/AlGaAs 2 dimensional electron gas (2DEG) heterostructure micro-Hall probe (HP) with a spatial resolution of $\sim 0.8\,\mu$m, was used as the sensing element.[2)] In spite of the excellent results obtained using this RT-SHPM system, further improvements in the spatial resolution of the GaAs/AlGaAs HP are necessary for imaging on the nanometer scale. Our experience of fabricating GaAs/AlGaAs Hall probes led us to conclude that, even if state of the art lithography is used to fabricate sub-0.5 $\mu$m features, the use of such probes in a RT-SHPM will be ultimately impractical due to surface charge depletion effects that limit the maximum Hall probe drive current (the maximum drive current for a $\sim 1.0\,\mu$m HP at room temperature was between 2–4 $\mu$A) and hence its magnetic field sensitivity.[3)] Also, the high series resistance of such 2DEG sensors leads to high thermal noise (Johnson noise) which in turn degrades the signal to noise ratio at room temperature.

In this paper, we report on an alternative approach to scanning Hall probe microscopy room temperature by employing a micro-Hall probe sensing element fabricated using bismuth (Bi), a semi-metal having a carrier concentration five orders of magnitude lower than metals and the advantage over semiconductors of negligible surface charge depletion effects.[4,5)] We describe the fabrication of bismuth micro-Hall probes (Bi-HP) with integrated scanning tunnelling microscope (STM) tips and demonstrate for the first time, that by incorporating the Bi-HP into the RT-SHPM system, it is possible to directly image magnetic domains of garnet thin films and demagnetized strontium ferrite permanent magnets. Further, a comparison of room temperature device figures of merit such as Johnson noise, showed the magnetic field sensitivity of Bi probes to be comparable to that of semiconducting GaAs/AlGaAs heterostructure micro-Hall probes under the measurement conditions described. We conclude that Bi is a practical alternative choice of material for the fabrication of nanometer-scale Hall probes for RT-SHPM imaging of magnetic domain structures.

The Bi-HP used in this study were processed using a procedure similar to that used for fabricating the GaAs-HPs as described previously.[2)] The integrated STM-tip was used for precise vertical positioning as well as topographic imaging during RT-SHPM measurements.

The Bi-HP were fabricated on 5 mm $\times$ 5 mm, semi-insulating (100) GaAs substrates by the following procedure: (i) evaporation of a 70 nm thick Bi Hall bar element onto the GaAs substrate through a patterned photoresist window from a thermally heated boat source in a vacuum of $1 \times 10^{-6}$ Torr, at a rate of 1 nm/sec; (ii) lift-off in acetone to define Bi-HP structure $\sim 13\,\mu$m away from the corner of the chip; (iii) photolithography and lift-off to define 400 $\mu$m $\times$ 400 $\mu$m bonding pads (30 nm Cr/150 nm Au); (iv) patterning to define STM-tip pad, consisting of a window overlapping a one micron deep mesa at the chip corner; (v) deposition of STM-tip metals (15 nm Cr/20 nm Au) by thermal evaporation at $1 \times 10^{-6}$ Torr.

The electrical continuity of the resulting Bi-HP was checked and the chips mounted and bonded onto packages using 12 $\mu$m Au wires for incorporation into the RT-SHPM system. The main components of the RT-SHPM system and a typical Bi-HP are shown in Figs. 1 and 2, respectively.

A Bi micro-Hall probe sensor with a spatial resolution of $\sim 2.8\,\mu$m, that is the size of the 'Hall-cross' at the intersection of the 4 leads, was mounted onto a piezoelectric scanning tube (PZT) at a tilt angle of 1.5° with respect to the sample surface. The procedure for magnetic imaging consisted of initially using a combination of high-resolution stepper motors (coarse) and the PZT (fine) to position the HP in close proximity to the sample surface until a tunnel current was detected. After a stable tunnel current was established, the Bi-HP was scanned over the surface while simultaneously mon-

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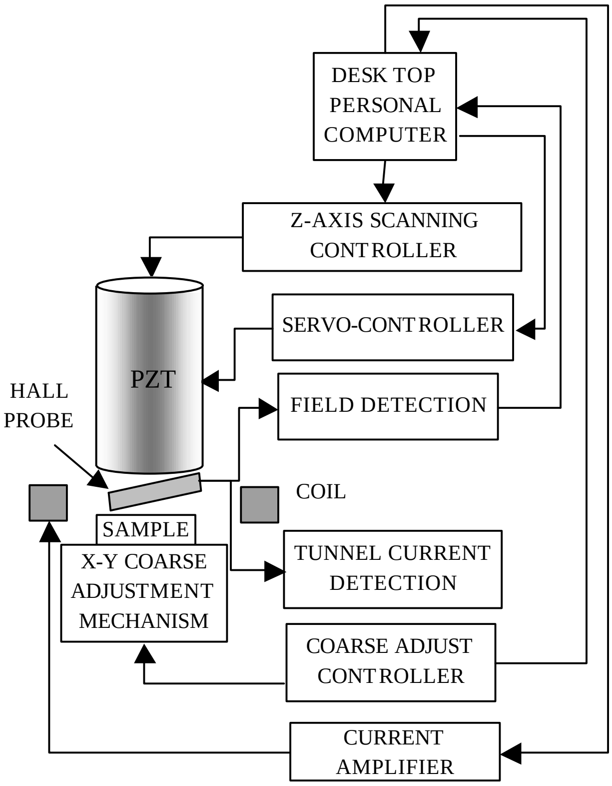


Fig. 1. The main components of the RT-SHPM system.

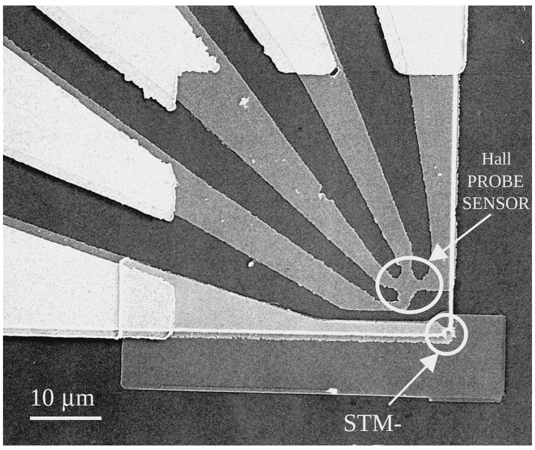


Fig. 2. A typical bismuth micro-Hall probe and integrated STM-tip.

itoring changes in Hall voltage due to fluctuations of the perpendicular component of the magnetic field emanating from the scanned surface.

The design of the RT-SHPM system enables three modes for data acquisition: (a) the *FAST RT-SHPM mode*, where only the Bi-HP output is monitored and displayed during measurement; (b) the *STM/RT-SHPM mode*, where the STM tip tunnel current and Bi-HP signal are both monitored, for the simultaneous measurement of surface topography and corresponding magnetic field fluctuations; (c) *REAL-TIME RT-SHPM mode*, where the entire measurement is completed before the magnetic image is displayed, for ultra-high speed scans of up to 1 frame per second. The black and white regions of RT-SHPM scan images represent magnetic domains with magnetizations into and out of the plane of the paper. For colored 3D visualization and animation of the raw black and white image data, we developed a unique set of program routines using the Interactive Data Language.[6)]

The Hall coefficient ($R_H$) and series resistance ($R_s$) of the Bi-HP were measured to be $3.3 \times 10^{-4}$ Ω/G and 2 kΩ, respectively. The magnetic field resolution, that is, signal to noise ratio ($S/N$) of a Hall probe can be defined as,

$$\frac{S}{N} = \frac{(I_H R_H B)}{\sqrt{4k_B T R_s \Delta f}},$$

where, $I_H$ is the Hall probe driving current, $B$ is the magnetic induction being measured, $\Delta f$ is the measurement band width, $k_B$ is Boltzmann's constant, and $T$ is measurement temperature. In this equation, $\sqrt{4k_B T R_s \Delta f}$, is the Johnson noise and main component of the measurement noise and $(I_H R_H B)$, the Hall voltage at a given drive Hall current and applied field. Using a spectrum analyzer, the Johnson noise of the Bi-HP was measured to be 100 nV/$\sqrt{\text{Hz}}$ at a maximum driving Hall current of 800 $\mu$A Hall and the resulting $S/N$ ratio was determined to be 0.38 G/$\sqrt{\text{Hz}}$. A small $1/f$ noise component was also observed.

For comparison with semiconducting Hall probes, similar noise measurements were carried out on a GaAs/AlGaAs micro-Hall probe with a physical size of 1.2 $\mu$m $\times$ 1.2 $\mu$m and with $R_H$ and $R_S$ of 0.26 Ω/G and 70 kΩ, respectively. The Johnson noise of the GaAs/AlGaAs HP was measured to be 316 nV/$\sqrt{\text{Hz}}$ at a maximum driving Hall current of 2 $\mu$A Hall and the resulting $S/N$ ratio was to be 0.41 G/$\sqrt{\text{Hz}}$. Again a $1/f$ noise component was also observed.

Thus the room temperature magnetic field sensitivity of the Bi-HP was superior to that of a semiconducting GaAs/AlGaAs heterostructure Hall probe. The better performance of the Bi-HP underscores the inherent noise problems associated with the high series resistance of the

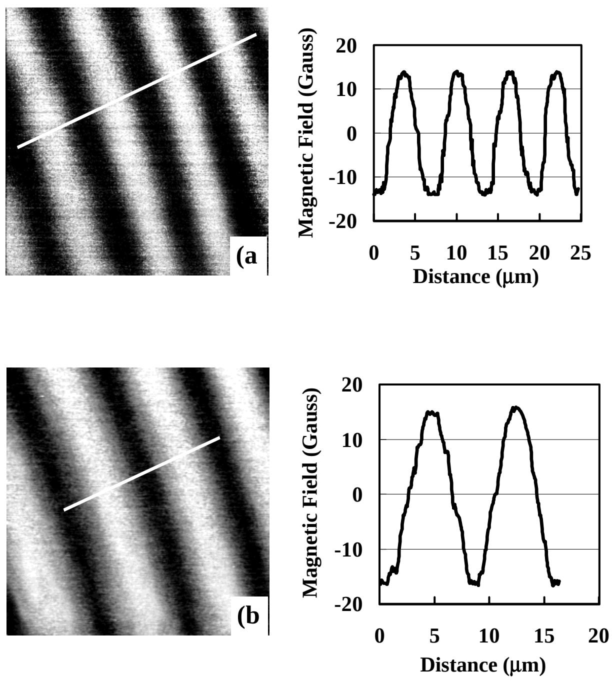


Fig. 3. 25 $\mu$m $\times$ 25 $\mu$m RT-SHPM images showing the changes in the stripe domain structure of a 5.5-$\mu$m thick bismuth substituted iron garnet thin film under perpendicular external bias fields of 1021 Oe (a) and 1131 Oe (b). The adjacent graphs show the cross-section field variations along lines.

GaAs/AlGaAs Hall probes at ambient temperatures.[7)]

All results described hereafter were obtained at a probe height of 0.5 $\mu$m using the *FAST-SHPM mode* ($\sim$ 15 s per frame) of the RT-SHPM with Hall probe drive currents between 200–400 $\mu$A. Self-induced magnetic fields in the Bi-HP due to drive currents, were calculated by integration of the Biot-Savart equation for magnetic induction[8)] and found to be less than 0.6 G, a value that is negligible compared with the fields being measured.

Figures 3(a) and 3(b) are 25 $\mu$m $\times$ 25 $\mu$m RT-SHPM images showing the changes in the stripe domain structure of a 5.5-$\mu$m thick bismuth substituted iron garnet thin film under perpendicular external bias fields of 1021 Oe and 1131 Oe, respectively. The graphs show the variation of the magnetic field along the lines drawn on the images. These results show one part of the process of configurational hysteresis of domain structures in low coercivity films with strong perpendicular magnetic anisotropy.[1)] The RT-SHPM will be a valuable tool for monitoring domains in garnet crystals used in the optical isolation industry.[9)]

Figures 4 is a RT-SHPM magnetic image of the surface of a polished 400-$\mu$m thick demagnetized strontium ferrite permanent magnet showing microscopic domain structures with fields varying as shown in the accompanying cross-section graph. Simultaneous STM-tip images, as shown in Fig. 5, showed the presence of surface roughness (maximum of 0.35 $\mu$m) due to the polishing process, but no correlation was observed between the magnetic and topographical images of the magnet surfaces. An interpretation of these results and a general deeper understanding of the physical properties of domain structures in ferrites is important for the development of high coercivity permanent magnets.[10)] We are currently carrying out a comparative study using a RT-SHPM (microscopic) and vibrating sample magnetometer (macroscopic) on the behavior of ferromagnetic domains in permanent magnets under large external pulsed magnetic fields (10 Tesla) with the aim of elucidating the affect of domain size and mobility, on the coercivity and saturation magnetization of the magnets.

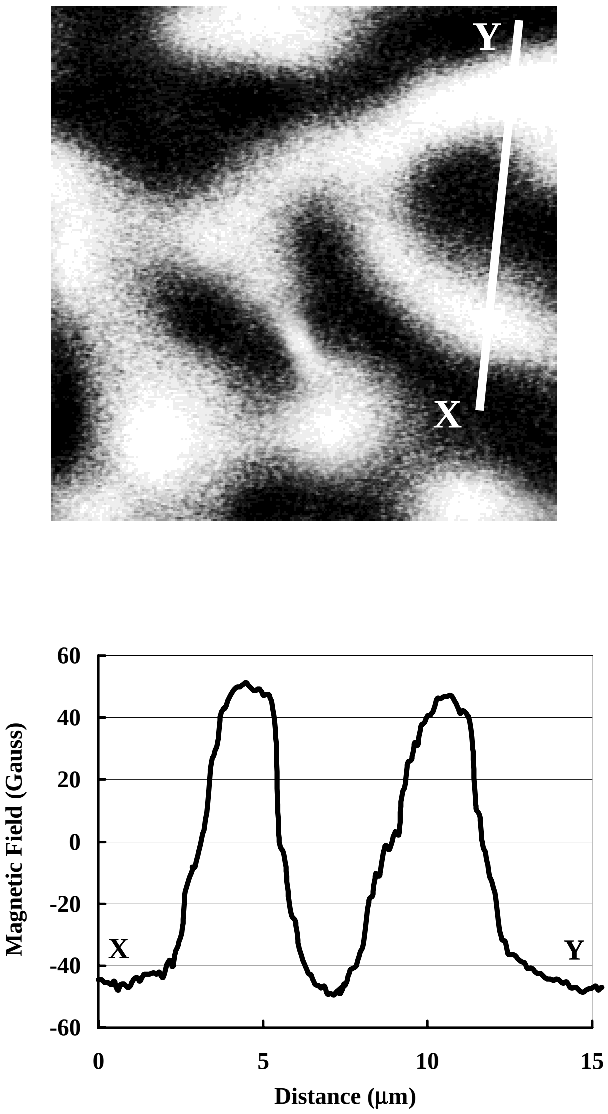


Fig. 4. A 25 $\mu$m $\times$ 25 $\mu$m RT-SHPM image of the domain structure observed in a demagnetized strontium ferrite permanent magnet. The graph shows the cross-section field variation along line X–Y.

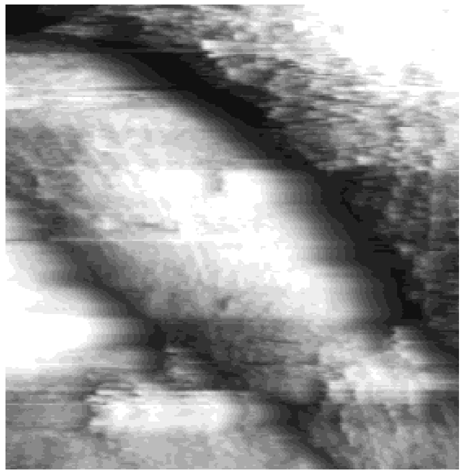

Fig. 5. 25 $\mu$m $\times$ 25 $\mu$m topographic image of the Sr ferrite permanent magnetic surface measured using the *STM/RT-SHPM mode*, where the STM tip tunnel current and Bi-HP signal are both monitored simultaneously. The surface roughness (0.32 $\mu$m) is due to the polishing process.

In summary, we demonstrated the successful use of Bi micro-Hall probes incorporated in a RT-SHPM for the direct magnetic imaging of domains structures in low coercivity garnets and demagnetized Sr ferrite permanent magnets. The magnetic field sensitivity at room temperature of the Bi-HP was found to be comparable to that of a GaAs/AlGaAs heterostructure Hall probe under optimized measurement conditions. Our results showed that Bi is a practical alternative to semiconducting material for the fabrication of nanometer scale Hall probes in order to overcome limitations associated with surface depletion effects of semiconducting micro-Hall probe sensors.

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